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# ERP Evidence for Cross-Modal Audiovisual Effects of Endogenous Spatial Attention within Hemifields

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## Abstract

■ Previous ERP studies have uncovered cross-modal interactions in endogenous spatial attention. Directing attention to one side to judge stimuli from one particular modality can modulate early modality-specific ERP components not only for that modality, but also for other currently irrelevant modalities. However, past studies could not determine whether the spatial focus of attention in the task-irrelevant secondary modality was similar to the primary modality, or was instead diffuse across one hemifield. Here, auditory or visual stimuli could appear at any one of four locations (two on each side). In different blocks, subjects judged stimuli at only one of these four locations, for an auditory (Experiment 1) or visual (Experiment 2) task. Early attentional modulations of visual

and auditory ERPs were found for stimuli at the currently relevant location, compared with those at the irrelevant location within the same hemifield, thus demonstrating within-hemifield tuning of spatial attention. Crucially, this was found not only for the currently relevant modality, but also for the currently irrelevant modality. Moreover, these within-hemifield attention effects were statistically equivalent regardless of the task relevance of the modality, for both the auditory and visual ERP data. These results demonstrate that within-hemifield spatial attention for one task-relevant modality can transfer cross-modally to a task-irrelevant modality, consistent with spatial selection at a multimodal level of representation. ■

## INTRODUCTION

Although traditional research on spatial attention has usually considered only one sensory modality at a time (e.g., just vision, hearing, or touch), more recent work has examined cross-modal interactions in spatial attention by means of multisensory studies (see Driver & Spence, 1998, for an overview). Behavioral studies have uncovered cross-modal interactions in both exogenous (e.g., McDonald, Teder-Sälejärvi, & Hillyard 2000; Spence & Driver, 1997; Ward, 1994) and endogenous (e.g., Spence & Driver, 1996; Spence, Pavani, & Driver, 2000) covert spatial attention. Functional imaging studies have begun to reveal cross-modal activations due to spatial attention (see Macaluso & Driver, 2001, for review). Event-related brain potential (ERP) methods have also revealed cross-modal interactions that relate to spatial attention, and have shown that these can affect early modality-specific ERP components, again for both exogenous (e.g., Kennett, Eimer, Spence, & Driver, 2001; McDonald & Ward, 2000) and endogenous cases (e.g., Eimer & Schröger, 1998; Hillyard, Simpson, Woods, VanVoorhis, & Münte, 1984). Here we focus on cross-modal audiovisual interactions in endogenous covert spatial attention, as studied with ERP measures.

Multimodal ERP experiments on endogenous spatial attention to date (e.g., Eimer & Schröger, 1998; Teder-Sälejärvi, Münte, Sperlich, & Hillyard, 1999; Eimer & Driver, 2000; Eimer, Cockburn, Smedley, & Driver, 2001; Eimer & Van Velzen, 2002; Eimer, Van Velzen, & Driver, 2002; Hillyard et al., 1984) have typically all used a similar paradigm, in which one modality serves as the “primary” modality for the task, while another modality is “secondary” because it is task-irrelevant. This primary/secondary paradigm typically requires covert attention to be endogenously directed to the left or right side, for judgements within just the primary (task-relevant) modality on that side. Another secondary (task-irrelevant) modality should be entirely ignored. A single stimulus is presented on each trial, unpredictably on the left or right side, in just one modality (unpredictably in the relevant/primary, or the irrelevant/secondary modality). Only a stimulus in the relevant primary modality on the attended side has to be discriminated.

The typical cross-modal finding from this general paradigm has been that attentional modulations of sensory-specific visual, auditory, or somatosensory ERP components can be observed not only when that particular modality serves the primary task-relevant role, but also when that modality is currently irrelevant/secondary, with attention being directed to one side in order to judge a different modality instead. Such results have suggested that relatively early stages of visual,

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auditory, and tactile information processing (i.e., stages traditionally considered to be “unimodal”) can be affected by cross-modal interactions in spatial attention (see Eimer, 2001; Eimer & Driver, 2001, for reviews).

The existence of such cross-modal ERP effects due to endogenous spatial attention is relevant for our understanding of the mechanisms underlying attentional processes, since it could suggest that selection of an attended location generally operates at a multimodal level of spatial representation (e.g., Farah, Wong, Monheit, & Morrow, 1989). We have recently obtained some evidence for this hypothesis when investigating ERPs elicited during anticipatory covert shifts of spatial attention, in response to central symbolic cues directing attention to the left or right side, towards the expected location of visual, auditory, or tactile events (Eimer, Van Velzen, & Driver, 2002, 2003). In these experiments, ERP components sensitive to the direction of a cued attentional shift were virtually indistinguishable during shifts of attention for a visual, auditory, or tactile task, suggesting that these components may reflect the selection of an attended spatial location at a multimodal level (see Eimer et al., 2002, for further discussion).

A further way to investigate the hypothesis that an attended location may be selected multimodally is to investigate how attention is spatially distributed across task-relevant and task-irrelevant modalities. On the hypothesis of multimodal spatial selection, the spatial distribution of attention for primary/relevant modalities should not differ systematically from that for secondary/irrelevant modalities. However, this issue has typically been overlooked by most previous cross-modal studies on endogenous spatial attention (including ERP work), because these have examined only one location in each hemifield (i.e., just one left and one right location). These cross-modal studies could not, therefore, examine the spatial distribution of covert attention for each modality *within* hemifields.

In the behavioral literature on unimodal visual attention, there have been some proposals that attention might operate in a hemifield-wide manner, selecting just left-sided or right-sided information (e.g., Hughes & Zimba, 1985, 1987). However, this idea has been discredited by many behavioral demonstrations that visual attention can be covertly directed to different locations *within a hemifield*, in a graded manner (e.g., Downing & Pinker, 1985; see also Egly & Homa, 1991). Moreover, in unimodal studies of purely visual attention, ERP data have also provided some evidence for finely tuned spatial gradients of covert visual attention within hemifields (e.g., Eimer, 1997; Mangun & Hilliard, 1988).

Some of the literature on auditory attention (e.g., see Rorden & Driver, 2001) has also considered whether attentional selectivity might operate in a hemifield-wide manner. Audition might, in principle, differ in this respect from vision, because of its reduced spatial acuity.

However, behavioral (e.g., Mondor & Zatorre, 1995; Rorden & Driver, 2001) and ERP data (e.g., Teder-Sälejärvi & Hillyard, 1998) have shown that spatial gradients of covert attention can arise *within* hemifields for audition as well as for vision. Finally, at least one cross-modal behavioral study has shown that exogenous effects of peripheral auditory cues on visual performance can be fairly specific to the cued location, rather than extending across the entire visual hemifield (Spence & Driver, 1998; see also Driver & Spence, 1999).

The aim of the present study was to investigate with ERPs whether such within-hemifield spatial tuning can transfer cross modally from a primary (i.e., currently task-relevant) modality to a secondary (task-irrelevant) modality, for cases of endogenous spatial attention, as predicted by the hypothesis that endogenous spatial selection operates at a multimodal level of representation. There might instead be systematic differences in the spatial distribution of attention for relevant versus irrelevant modalities, with any cross-modal effects potentially applying diffusely to an entire hemifield (unlike unimodal effects of attention within the task-relevant primary modality). This might be expected if such cross-modal effects merely reflected differences in hemispheric activation (see Kinsbourne, 1975). For example, if selecting a particular location in the left visual hemifield for one modality involves some right-hemisphere activation, this might spread to affect auditory areas in the right hemisphere, potentially resulting in spatially unspecific processing benefits for auditory stimuli within the entire left visual hemifield.

In contrast to previous cross-modal ERP studies, stimuli could now appear at any of *four* possible locations (two in the left and two in the right hemifield; at “outer” or “inner” locations on each side). Only one of these locations was relevant for the prescribed auditory task (Experiment 1), or visual task (Experiment 2). Stimuli at the other three locations were to be ignored in the currently relevant primary modality; while secondary modality stimuli were to be ignored regardless of their location.

On each trial, a visual or auditory stimulus was presented unpredictably on the left or right side at an eccentricity of either 21° (inner location) or 52° (outer location). In Experiment 1, audition was task-relevant, with participants having to discriminate auditory stimuli at one of the four locations (to detect and respond to occasional “oddball” targets there), while ignoring auditory stimuli at other locations, and all visual events regardless of their location. The relevant eccentricity (i.e., attend outer vs. attend inner) was specified prior to each block, and remained constant for several successive blocks. However, the relevant side for attending to that eccentricity (left vs. right) varied in a trial-by-trial manner, being specified by a central symbolic visual precue presented at the start of each trial. In Experiment 2, the roles of the two modalities were reversed (i.e., with

vision now becoming task-relevant for the peripheral judgements and audition becoming irrelevant). In all other respects, Experiment 2 had an equivalent procedure to Experiment 1.

The main aim of these experiments was to use ERPs in order to test whether spatial attention for the secondary modality is diffusely allocated to the entire hemifield within which spatial attention is endogenously focused within the primary modality; or whether instead, the secondary modality can show within-hemifield attentional effects analogous to those found for the primary task-relevant modality, as predicted by supramodal selection of a particular location. (Further, more intermediate possibilities for the relationship between the attentional focus in the primary and secondary modalities are considered in detail in our *Discussion*.)

To investigate the allocation of attention within currently relevant (primary) or irrelevant (secondary) modalities, visual and auditory ERPs were analyzed in two successive steps. In the “between-hemifields” analysis, ERPs to stimuli presented within the cued hemifield were compared with ERPs for uncued-hemifield stimuli, separately for currently relevant and irrelevant modalities. These between-hemifield analyses were expected to confirm findings from previous ERP studies on visual–auditory cross-modal interactions (e.g., Teder-Sälejärvi et al., 1999; Eimer & Schröger, 1998; Hillyard et al., 1984). Those studies had used only two possible stimulus locations, one in each hemifield, and thus also compared ERPs for the relevant versus irrelevant hemifield.

The second analysis was the most critical for the present issue concerning the spatial distribution of attention within and across modalities, and in particular for any within-hemifield effects of attention for the secondary task-irrelevant modality. This second analysis was confined to ERPs elicited in response to stimuli presented “within the cued hemifield” only. Here, we compared ERPs to stimuli presented at the relevant location (i.e., the inner location for attend inner blocks, and the outer location for attend outer blocks) to ERPs for stimuli presented within the cued hemifield, but at the other location on that side, which was to be ignored. For the relevant modality (audition in Experiment 1, and vision in Experiment 2), we expected to find systematic within-hemifield attentional modulations for relevant-eccentricity versus irrelevant-eccentricity stimuli, similar to previous observations from unimodal visual and unimodal auditory ERP studies (e.g., Teder-Sälejärvi & Hillyard, 1998; Eimer, 1997; Mangun & Hillyard, 1988). The critical new question was whether similar within-hemifield effects of spatial attention would also be observed for the currently irrelevant *secondary* modality (i.e., vision in Experiment 1, and audition in Experiment 2). If cross-modal effects of spatial attention merely reflect a diffuse hemifield-wide allocation for secondary modalities, within-hemifield attentional mod-

ulations should be entirely absent for these task-irrelevant modalities. Thus, in Experiment 1, there should be no differences between ERPs to visual stimuli at the location relevant for the auditory task, versus ERPs to visual stimuli presented in the same hemifield, but at the currently irrelevant location for audition on that side. An analogous prediction applied for auditory ERPs when this modality was irrelevant in Experiment 2.

By contrast, should within-hemifield attentional modulations of visual and auditory ERPs be found not only for primary modalities, but also when vision and audition are completely task-irrelevant, this would clearly be inconsistent with the diffuse hemifield-wide hypothesis. Such a finding might suggest that primary and secondary modalities have a similar spatial focus even within a single hemifield, as predicted by the hypothesis that spatial locations are selected at a multimodal level of representation.

## RESULTS

### Experiment 1: Audition Primary

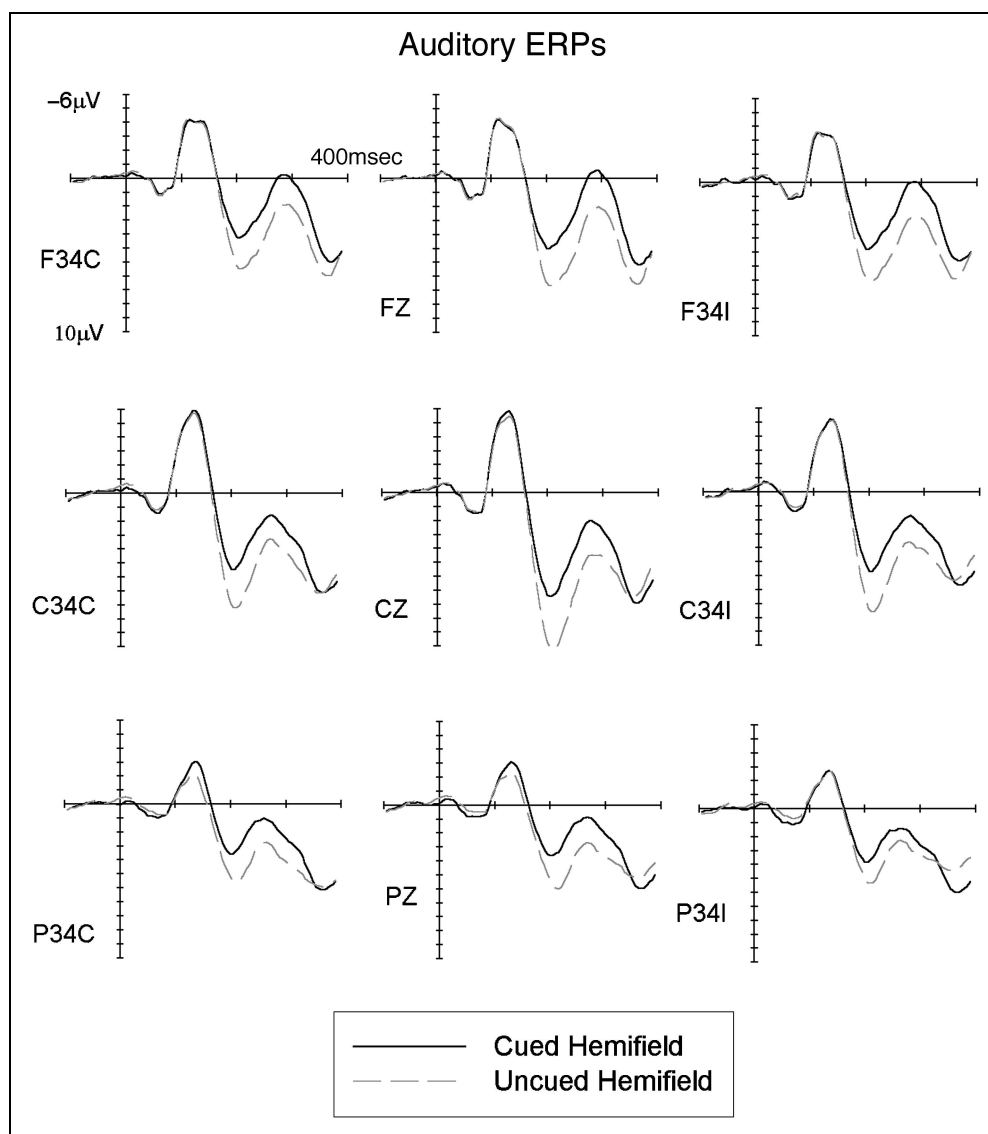
#### *Behavioral Performance*

Behavioral data are presented for completeness only, since the critical findings come from ERP data for stimuli that did not require any behavioral response. Vocal responses to occasional “oddball” auditory targets (i.e., those with gaps, unlike the more frequent standard auditory stimuli) at relevant locations were 563 and 577 msec (measured relative to the onset of the target-defining gap) in the attend inner and attend outer blocks, respectively; these latencies did not differ significantly,  $F(1,11) = 3.3$ ;  $p < .097$ . Participants missed 3.8% and 3% of all relevant targets for attend inner and attend outer blocks, with no significant difference. False alarms for trials with gap stimuli at irrelevant positions and for trials with no gap stimuli occurred on less than 1% of such trials.

#### *Unimodal Effects: ERPs for Auditory Stimuli (Primary Task-Relevant Modality)*

Figure 1 shows ERPs elicited by auditory nongap stimuli presented in the cued or uncued hemifield (averaging across stimulus eccentricities within these hemifields). Stimuli on the cued side elicited an enhanced negativity compared with uncued-hemifield stimuli, which started on the descending flank of the auditory N1 component, consistent with many previous ERP findings on auditory attention (e.g., Eimer & Schröger, 1998). In the Nde interval (130–200 msec poststimulus), this effect was reflected in main effects of cueing at lateral anterior and lateral central sites, as well as at Cz, all  $F(1,11) > 4.8$ ; all  $p < .05$ . In the subsequent Ndl interval (200–300 msec), significant main effects of cueing were obtained at all recording sites, all  $F(1,11) > 11.5$ ; all

**Figure 1.** Grand-averaged auditory ERPs elicited in Experiment 1 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to auditory nongap stimuli presented in the cued hemifield (black solid lines) and in the uncued hemifield (gray dashed lines). Data are collapsed across inner and outer locations.



$p < .006$ . Stimulus eccentricity (auditory stimuli at inner vs. outer locations) did not significantly affect auditory ERP waveforms, and no significant Cueing  $\times$  Stimulus eccentricity interactions were obtained, all  $F(1,11) < 1.1$ .

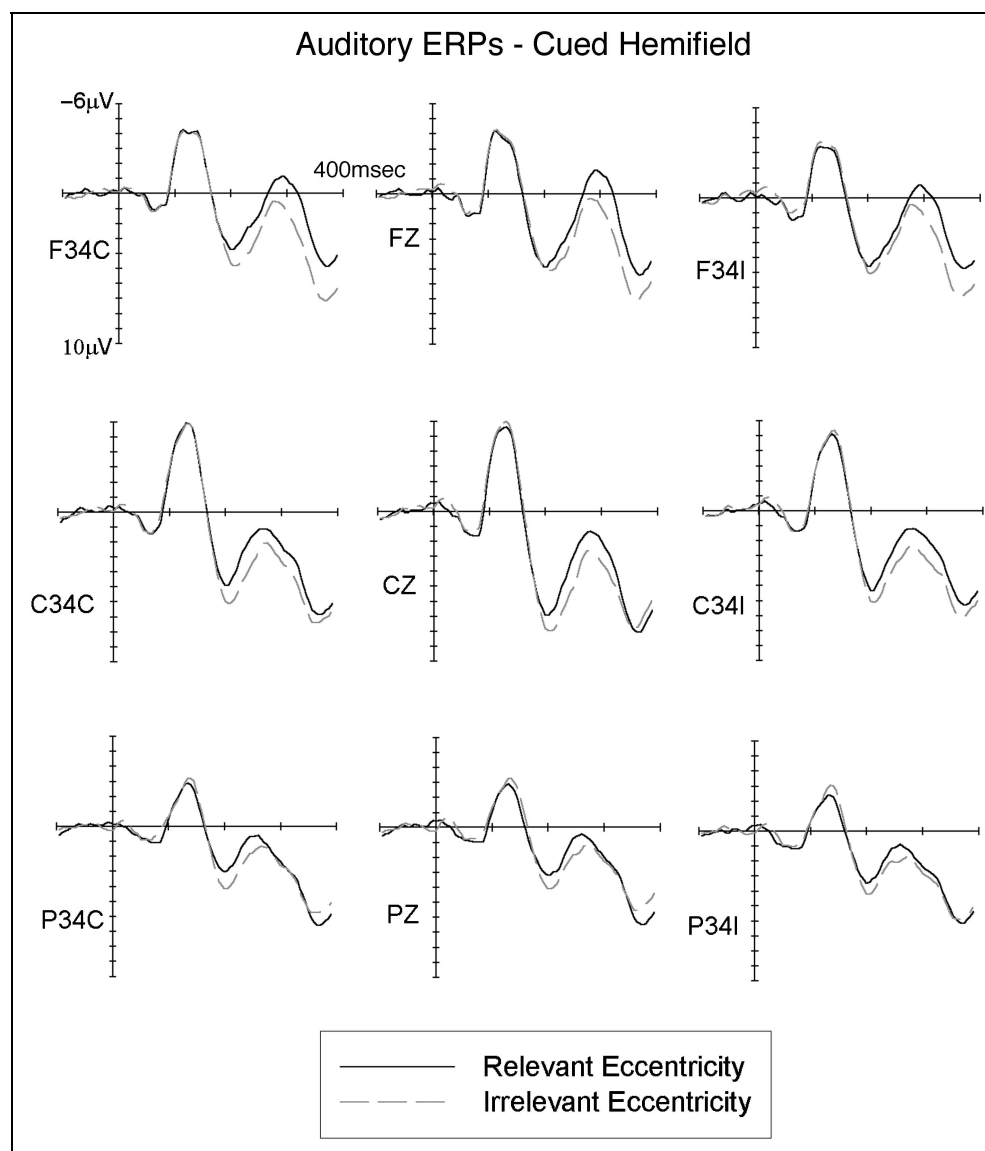
Figure 2 shows ERPs in response to auditory stimuli presented “within the cued hemifield only,” displayed separately for stimuli at the currently relevant location within this hemifield (i.e., inner during attend inner blocks, and outer during attend outer blocks) versus for stimuli at the currently irrelevant eccentricity on that side. An enhanced negativity was present for auditory stimuli at the currently relevant within-hemifield location, but the onset of this effect appeared to be somewhat delayed relative to the between-hemifield attentional effects shown in Figure 1. This was substantiated by statistical analyses, which failed to reveal any effect of whether stimuli were at the currently relevant or irrelevant within-hemifield location for the early Nde interval. In contrast, for the subsequent Nd1 interval,

enhanced negativities for auditory stimuli at relevant locations within the cued hemifield were reflected in significant effects of within-hemifield attention at lateral anterior, lateral central, and midline sites, all  $F(1,11) > 6.0$ ; all  $p < .032$ . No interactions between stimulus eccentricity and within-hemifield attention were present, all  $F(1,11) < 1$ , indicating that within-hemifield attentional selectivity applied comparably for auditory stimuli at inner and outer locations.

#### *Cross-Modal Effects: ERPs for Visual Stimuli (Secondary Task-Irrelevant Modality)*

Figure 3 shows ERPs elicited by visual stimuli presented in the hemifield that was cued versus uncued for the “auditory” task. There were no main effects of stimulus side, or interactions between stimulus side and cueing. Directing attention to one side for auditory judgments resulted in systematic modulations of visual

**Figure 2.** Grand-averaged auditory ERPs elicited in Experiment 1 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to auditory nongap stimuli presented within the cued hemifield, and are displayed separately for the currently task-relevant eccentricity (inner for attend inner blocks; outer for attend outer blocks; black solid lines), and for the currently irrelevant eccentricity (inner for attend outer blocks; outer for attend inner blocks; gray dashed lines).



ERPs, thus reflecting cross-modal influences of spatial attention from audition to vision. This did not significantly affect the P1 component at lateral posterior sites (see also Eimer & Schröger, 1998; Hillyard et al., 1984), but did reliably modulate the N1 component. Highly significant effects of cueing were present between 120 and 160 msec poststimulus at the lateral anterior, lateral central, and midline sites, all  $F(1,11) > 7.3$ ; all  $p < .02$ , reflecting an enhancement of the anterior N1 component in response to visual stimuli presented in the hemifield that was cued for the auditory task (Figure 3). Between 160 and 200 msec, effects of cueing were present not only at these sites, all  $F(1,11) > 18.1$ ; all  $p < .001$ , but also at the lateral posterior electrodes,  $F(1,11) = 18.1$ ;  $p < .001$ , reflecting effects of cross-modal attention on the lateral posterior N1. No cross-modal effects on visual ERPs were obtained in the subsequent analysis window (200–300 msec poststimu-

lus), again replicating earlier findings (e.g., Eimer & Schröger, 1998).

Stimulus eccentricity had a significant effect on the posterior N1 between 160 and 200 msec poststimulus, with larger N1 components in response to visual stimuli at inner as compared to visual stimuli at outer locations,  $F(1,11) = 9.9$ ;  $p < .01$ ; not shown in figures, consistent with retinal factors. More importantly, there was no Stimulus eccentricity  $\times$  Cueing interaction,  $F(1,11) < 1$ .

Figure 4 shows ERPs in response to visual stimuli presented within the cued hemifield (i.e., only on the side that was cued for the auditory task), displaying these separately for stimuli at the location that was currently relevant for the auditory task (i.e., inner under attend inner instructions, and outer under attend outer instructions), versus for stimuli at the irrelevant eccentricity on the same side. As can be

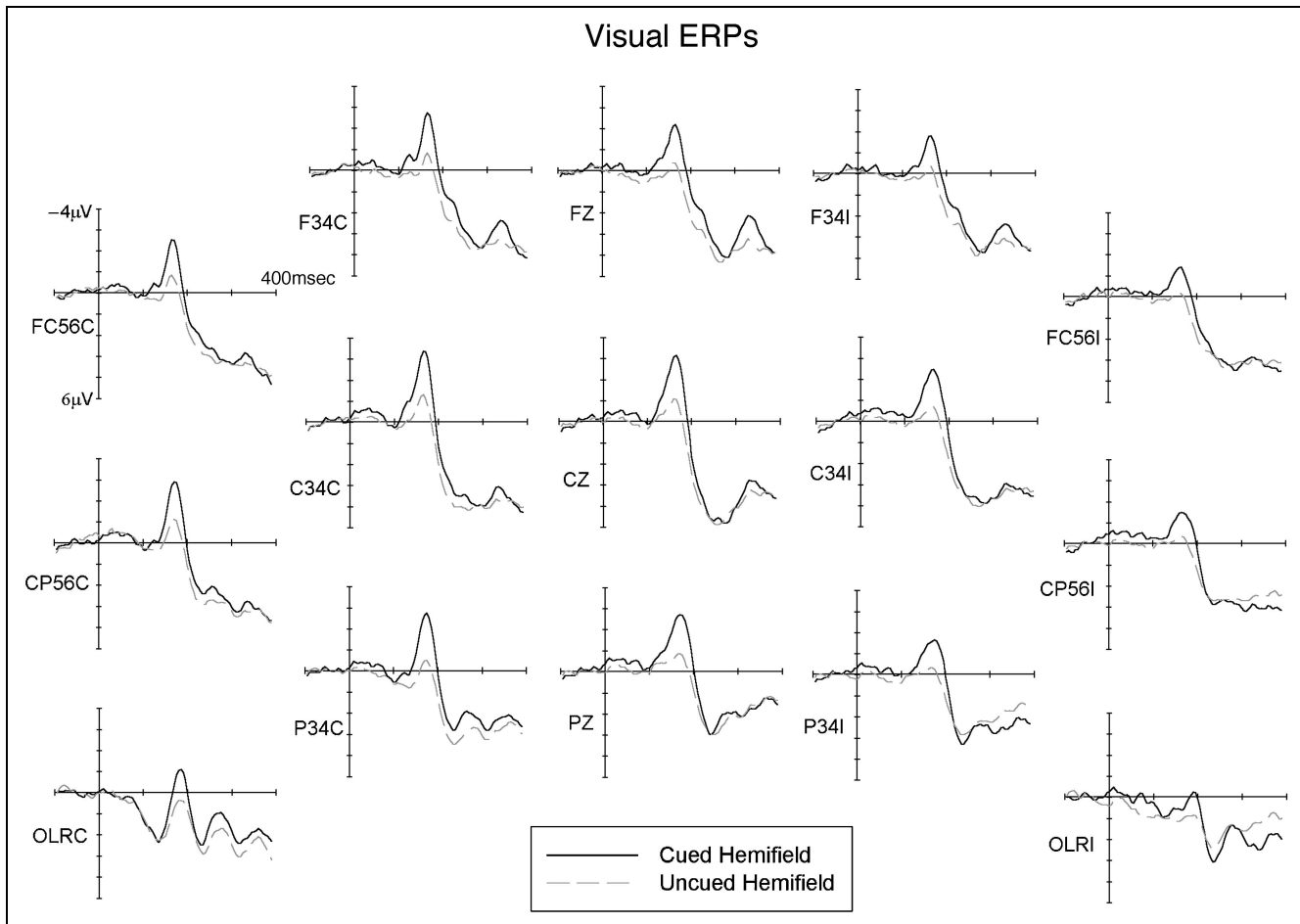
seen from Figure 4, cross-modal modulations of the anterior and posterior visual N1 components by spatial attention were clearly present even *within* the cued hemifield, with enhanced N1 amplitudes in response to visual stimuli presented at the relevant location for the auditory task, as compared to the currently irrelevant location in the same hemifield. This was reflected by main effects of within-hemifield attention at the lateral anterior, central, and posterior electrodes, and at midline sites, between 120 and 160 msec, all  $F(1,11) > 4.8$ ; all  $p < .05$ , as well as between 160 and 200 msec poststimulus, all  $F(1,11) > 13.5$ ; all  $p < .004$ . This demonstrates for the first time a cross-modal transfer of within-hemifield endogenous attentional tuning from audition to vision, with ERPs. Importantly, there were no significant interactions between stimulus eccentricity and within-hemifield attention between 160 and 200 msec poststimulus, all  $F(1,11) < 2.3$ ; all  $p < .15$ , indicating that these cross-modal within-hemifield attentional effects on the posterior visual N1 component applied comparably for visual stimuli at

inner and outer locations.<sup>1</sup> No effects of cross-modal within-hemifield attention on visual ERPs were present in the 200–300 msec poststimulus analysis window.

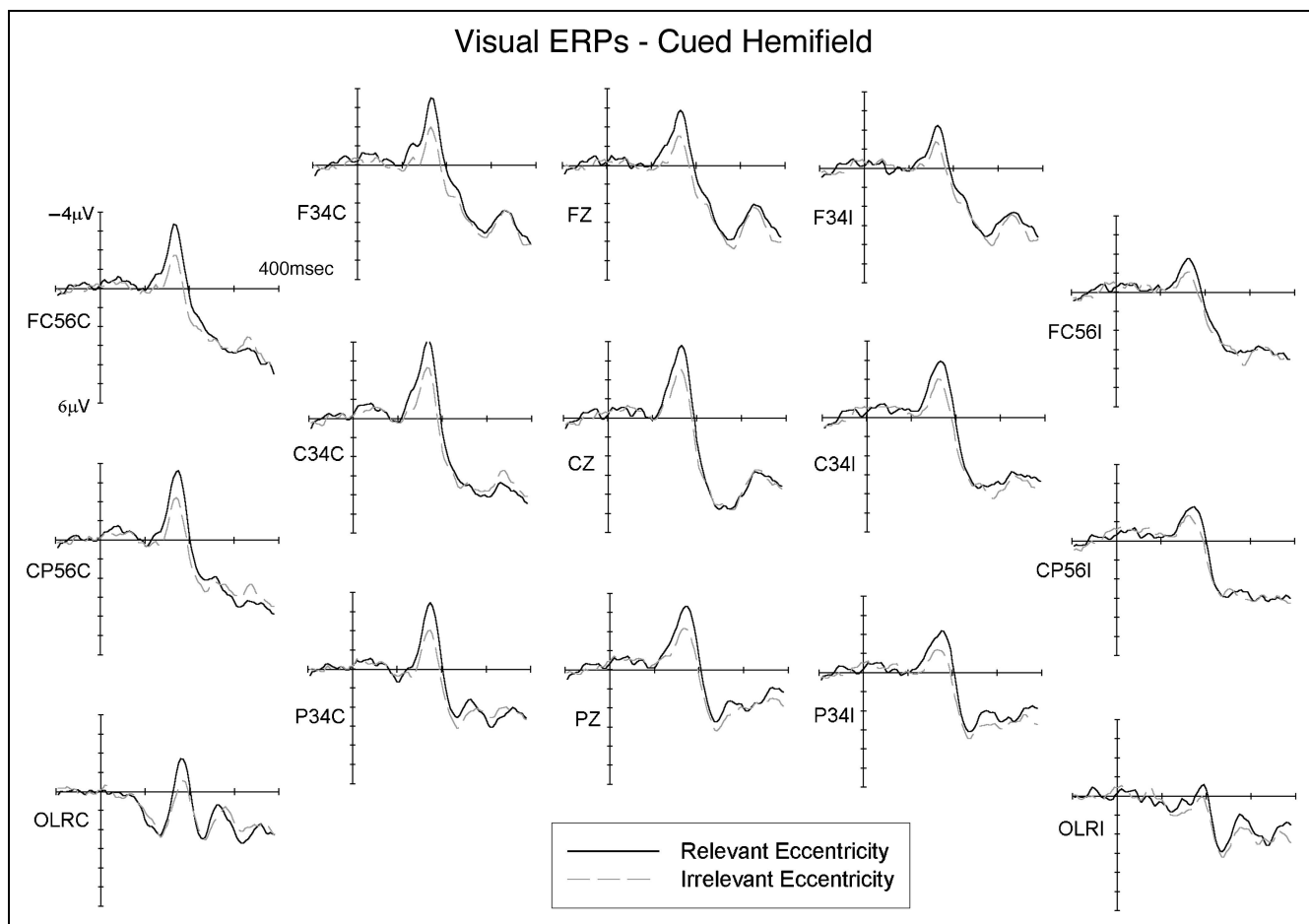
## Experiment 2: Vision Primary

### Behavioral Performance

Once again behavioral data are presented for completeness only, as the critical results concern ERP data for stimuli that required no behavioral response. Vocal responses to visual gap targets at the currently relevant location were somewhat faster (measured relative to the onset of the target-defining gap) in the attend inner blocks than in the attend outer blocks [568 vs. 608 msec;  $F(1,11) = 13.1$ ;  $p < .004$ ], consistent with retinal factors. Participants missed 8.5% and 8.2% of all relevant targets for attend inner and attend outer blocks, with no significant difference. More false alarms to visual nontargets at the currently relevant location were recorded in the attend outer condition than in the attend inner condition [4.1% vs. 1.1%;  $t(11) = 3.36$ ;  $p < .01$ ].



**Figure 3.** Grand-averaged visual ERPs elicited in Experiment 1 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to task-irrelevant visual stimuli presented in the cued hemifield (black solid lines) and in the uncued hemifield (gray dashed lines). Data are collapsed across inner and outer locations.



**Figure 4.** Grand-averaged visual ERPs elicited in Experiment 1 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to task-irrelevant visual stimuli presented within the cued hemifield, and are displayed separately for the eccentricity relevant for the auditory task (inner for attend inner blocks; outer for attend outer blocks; black solid lines) and for the task-irrelevant eccentricity (inner for attend outer blocks; outer for attend inner blocks; gray dashed lines).

.006]. False alarms in response to visual stimuli at irrelevant locations, or to auditory stimuli, occurred on less than 1% of these trials.

#### *Unimodal Effects: ERPs for Visual Stimuli (Primary Task-Relevant Modality)*

Figure 5 shows ERPs elicited by visual nongap stimuli presented in the cued or uncued hemifield (averaging across stimulus eccentricities within these hemifields). There were no main effects of stimulus side, or interactions between stimulus side and cueing. As would be expected, directing attention to the cued hemifield for the visual task resulted in systematic modulations of visual ERP components. A main effect of cueing was found for the P1 component at the lateral posterior sites,  $F(1,11) = 7.5$ ;  $p < .02$ , reflecting an enlarged P1 for visual stimuli presented in the cued hemifield. Significant effects of cueing were also present between 120 and 160 msec poststimulus at the lateral central and midline sites, both  $F(1,11) > 6.1$ ; both  $p < .032$ , and between 160 and 200 msec at all recording sites, all

$F(1,11) > 12.2$ ; all  $p < .005$ , reflecting attentional enhancements of both anterior and posterior N1 components (see Figure 5). Main effects of cueing were also observed between 200 and 300 msec poststimulus at all recording sites, all  $F(1,11) > 6.8$ ; all  $p < .024$ , reflecting a sustained enhanced negativity for visual stimuli in the cued hemifield relative to visual stimuli in the uncued hemifield (Figure 5). As in Experiment 1, the posterior visual N1 component was enhanced in response to visual stimuli at inner locations compared with visual stimuli at outer locations (not shown in figures), consistent with retinal factors. Although the main effect of stimulus eccentricity only approached significance across all the lateral posterior electrodes,  $F(1,11) = 4.2$ ;  $p < .07$ , a significant effect of stimulus eccentricity was present at the lateral occipital sites,  $F(1,11) = 11.0$ ;  $p < .01$ . However, no Stimulus eccentricity  $\times$  Cueing interaction was observed here,  $F(1,11) < 1$ .

Figure 6 shows ERPs in response to visual stimuli presented “within the cued hemifield only,” displaying these separately for stimuli at the relevant location within this hemifield (i.e., inner under attend inner

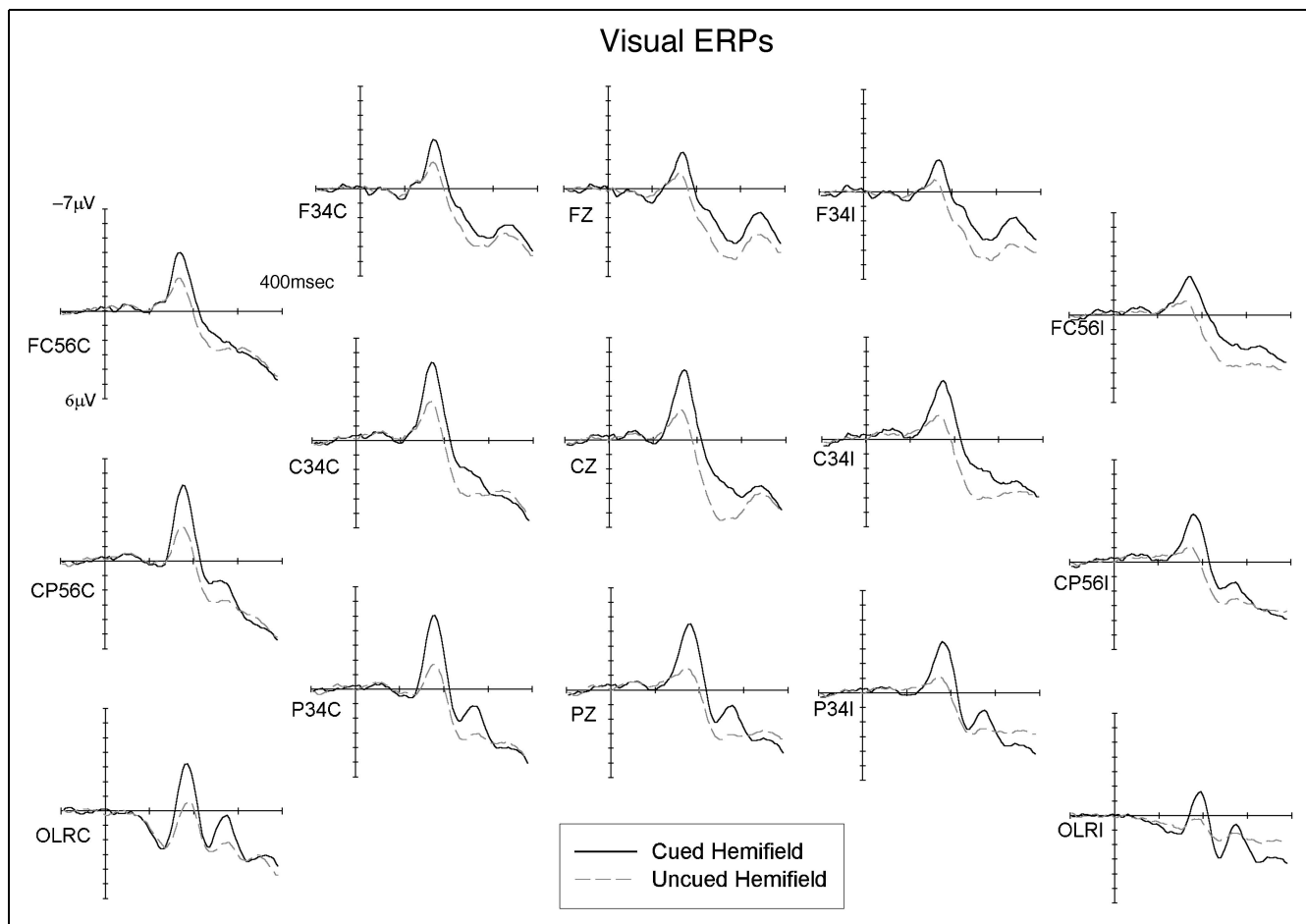


instructions, and outer under attend outer instructions), versus for stimuli at the currently irrelevant eccentricity on that side. In contrast to the between-hemifields analysis just presented, no effect of within-hemifield attention was found for the P1 component. However, attentional modulations of the anterior and posterior visual N1 components were clearly present within the cued hemifield, with enhanced N1 amplitudes in response to visual stimuli presented at the relevant location versus the currently irrelevant location on the same side. This was reflected by main effects of within-hemifield attention at the lateral central electrodes and at Cz between 120 and 160 msec, both  $F(1,11) > 5.0$ ; both  $p < .047$ ; and at all recording sites between 160 and 200 msec poststimulus, all  $F(1,11) > 9.8$ ; all  $p < .01$ . There were no interactions between stimulus eccentricity and within-hemifield attention in either of these time windows, all  $F(1,11) < 1.3$ , thus indicating that within-hemifield attentional effects on visual N1 components applied comparably for visual stimuli at inner and at outer locations. Finally, in the 200–300 msec poststimulus analysis window, effects of within-hemifield attention

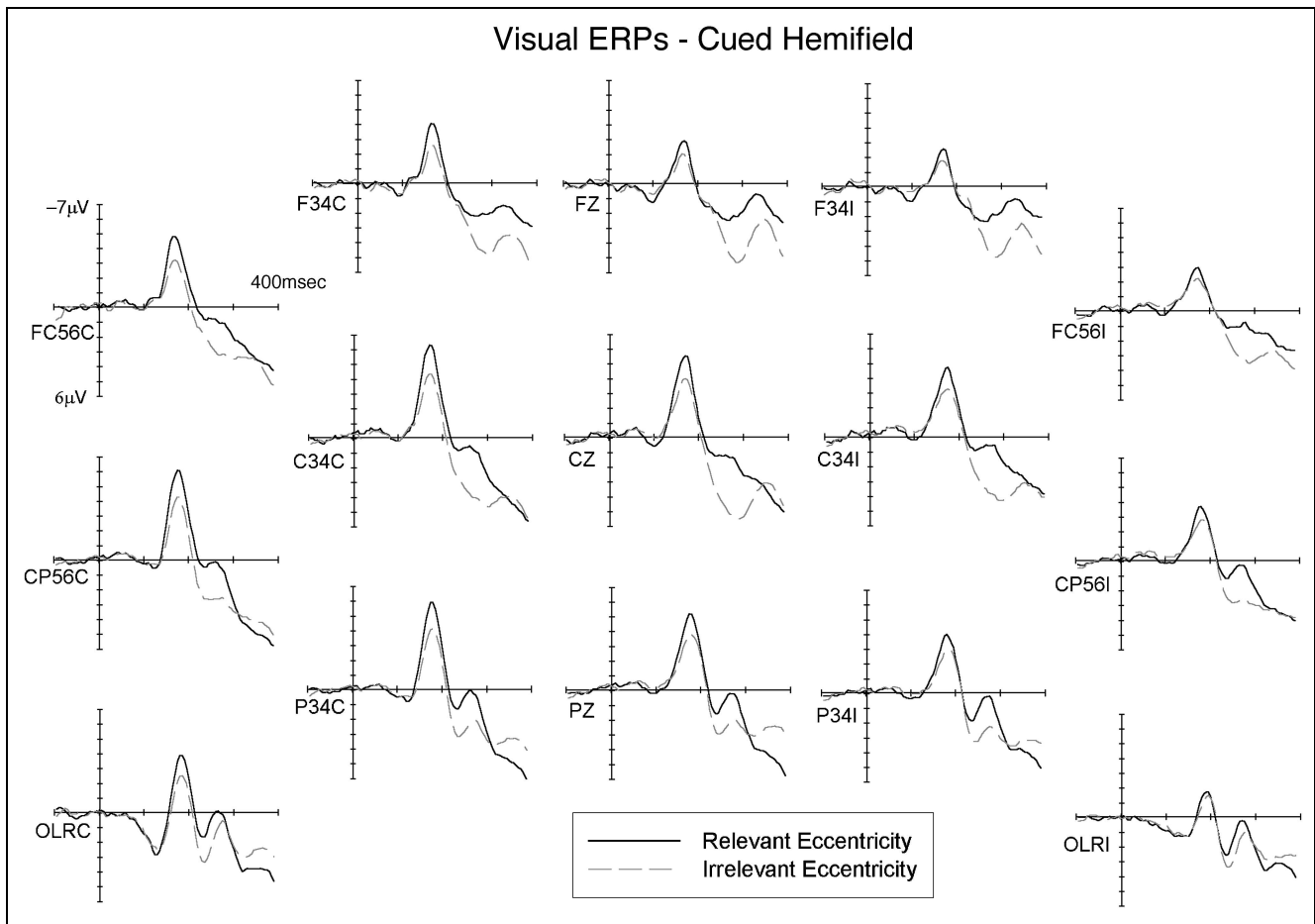
were present at the lateral anterior, lateral central, and midline electrodes, all  $F(1,11) > 5.6$ ; all  $p < .036$ , reflecting a sustained attentional negativity to visual stimuli at relevant locations within the attended hemifield (Figure 6), which did not interact with stimulus eccentricity, all  $F(1,11) < 1.2$ .

#### *Cross-Modal Effects: ERPs for Auditory Stimuli (Secondary Task-Irrelevant Modality)*

Figure 7 shows ERPs elicited by auditory stimuli in the cued versus uncued hemifield (averaging across stimulus eccentricities within these hemifields). Similar to Experiment 1, where the auditory stimuli had been task-relevant rather than irrelevant as now, stimuli on the cued side elicited an enhanced negativity compared with stimuli in the uncued hemifield. This effect again started on the descending flank of the auditory N1 component, reflecting cross-modal links in spatial attention from vision to audition. In the Nde interval (130–200 msec poststimulus), this cross-modal effect was reflected in main effects of cueing at the lateral anterior,



**Figure 5.** Grand-averaged visual ERPs elicited in Experiment 2 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to visual nongap stimuli presented in the cued hemifield (black solid lines) and in the uncued hemifield (gray dashed lines). Data are collapsed across inner and outer locations.



**Figure 6.** Grand-averaged visual ERPs elicited in Experiment 2 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to visual nongap stimuli presented within the cued hemifield, and are displayed separately for visual stimuli at the currently task-relevant eccentricity (inner for attend inner blocks; outer for attend outer blocks; black solid lines), and for visual stimuli at the irrelevant eccentricity (inner for attend outer blocks; outer for attend inner blocks; gray dashed lines).

lateral central, and midline sites, all  $F(1,11) > 8.3$ ; all  $p < .015$ . In the subsequent Ndl interval (200–300 msec), significant main effects of cueing were again obtained at these recording sites, all  $F(1,11) > 5.2$ ; all  $p < .043$ . As in Experiment 1, no main effects of stimulus eccentricity (auditory stimuli at inner vs. outer locations) were present, and no significant Cueing  $\times$  Stimulus eccentricity interactions were obtained, all  $F(1,11) < 1.8$ .

Figure 8 shows ERPs in response to auditory stimuli presented “within the cued hemifield only,” displayed these separately for stimuli at the location that was currently relevant for the visual task within this hemifield (i.e., inner for attend inner blocks; outer for attend outer blocks), versus for auditory stimuli at the currently irrelevant eccentricity for vision on the same side. An enhanced negativity, overlapping with the descending flank of the N1 component, was present for auditory stimuli presented at visually relevant compared with visually irrelevant locations “within” the cued hemifield. Main effects of within-hemifield attention were observed in the Nde interval (130–200 msec poststimulus) at the

lateral anterior, lateral central, and midline sites, all  $F(1,11) > 5.3$ ; all  $p < .042$ . This demonstrates for the first time a within-hemifield cross-modal effect from vision to audition for endogenous spatial attention, with the ERP measures revealing that this can affect relatively early auditory components (i.e., descending flank of N1). In the subsequent Ndl interval (200–300 msec poststimulus), main effects of within-hemifield attention were again present at the lateral anterior electrodes and at Fz, both  $F(1,11) > 6.8$ ; both  $p < .024$ , but not at more posterior electrodes. No interactions between stimulus eccentricity and within-hemifield attention were observed in the Nde and Ndl intervals, all  $F(1,11) < 1$ , suggesting that cross-modal within-hemifield attention effects on auditory ERPs applied comparably for auditory stimuli at inner and at outer locations.

## DISCUSSION

Although there is now unequivocal evidence for the existence of cross-modal interactions in spatial attention,

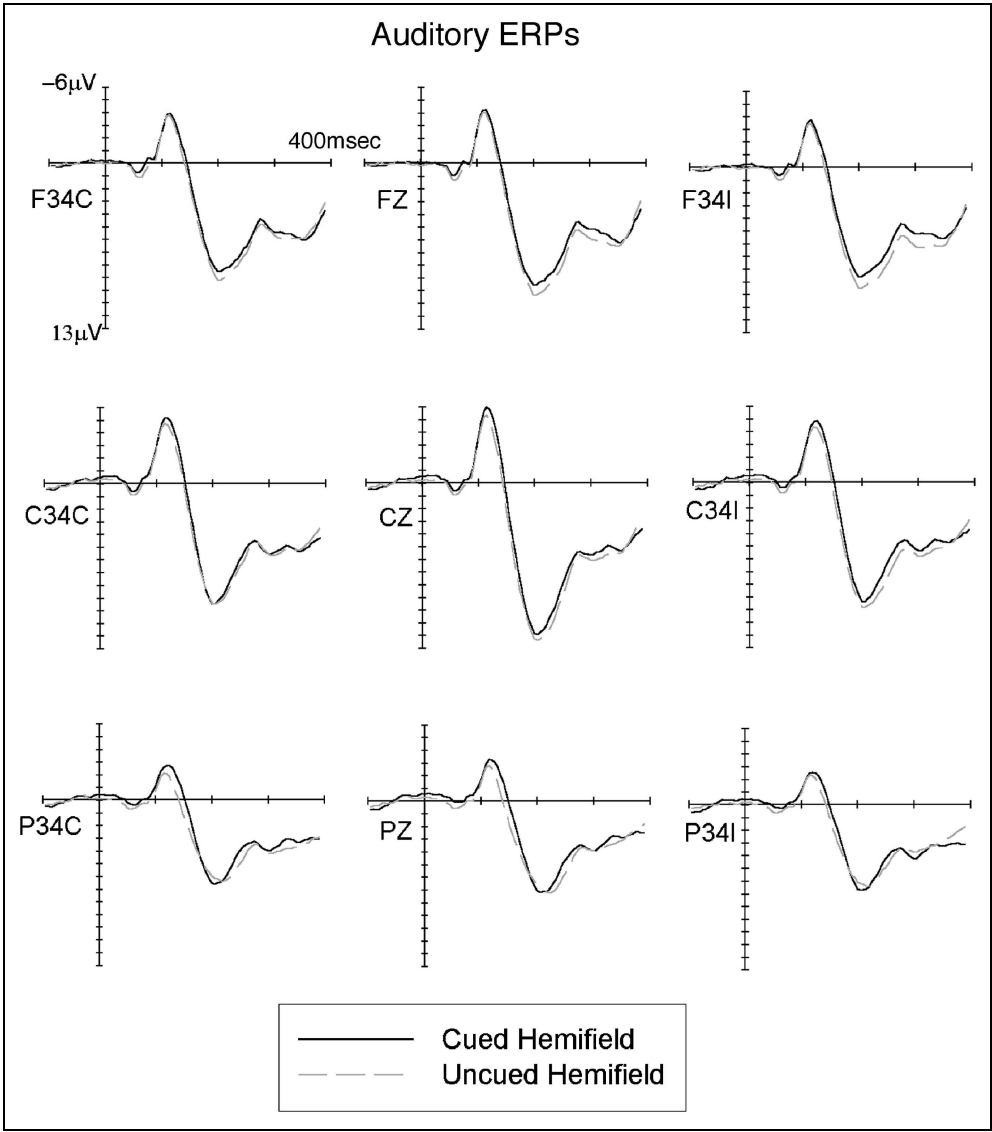
little is as yet known about the mechanisms underlying such interactions, or about their detailed spatial nature. One fundamental question for research on spatial attention is whether attended locations are selected at a multimodal level of spatial representation, or whether the spatial selection of visual, auditory, or tactile events is based on separate, modality-specific representations. The present study provides an initial ERP investigation of the spatial tuning of attentional selectivity for a currently relevant modality within hemifields; and in particular, the cross-modal transfer of this attentional focus to another irrelevant modality. If spatial locations were selected supramodally, one would expect to find no systematic differences in the spatial distribution of attention for relevant and irrelevant modalities. By contrast, if cross-modal effects on a currently task-irrelevant (secondary) modality reflect diffuse hemifield-wide attentional modulations for that modality, then no within-hemifield effects of attention should be found for it,

unlike what is observed for the primary task-relevant modality.

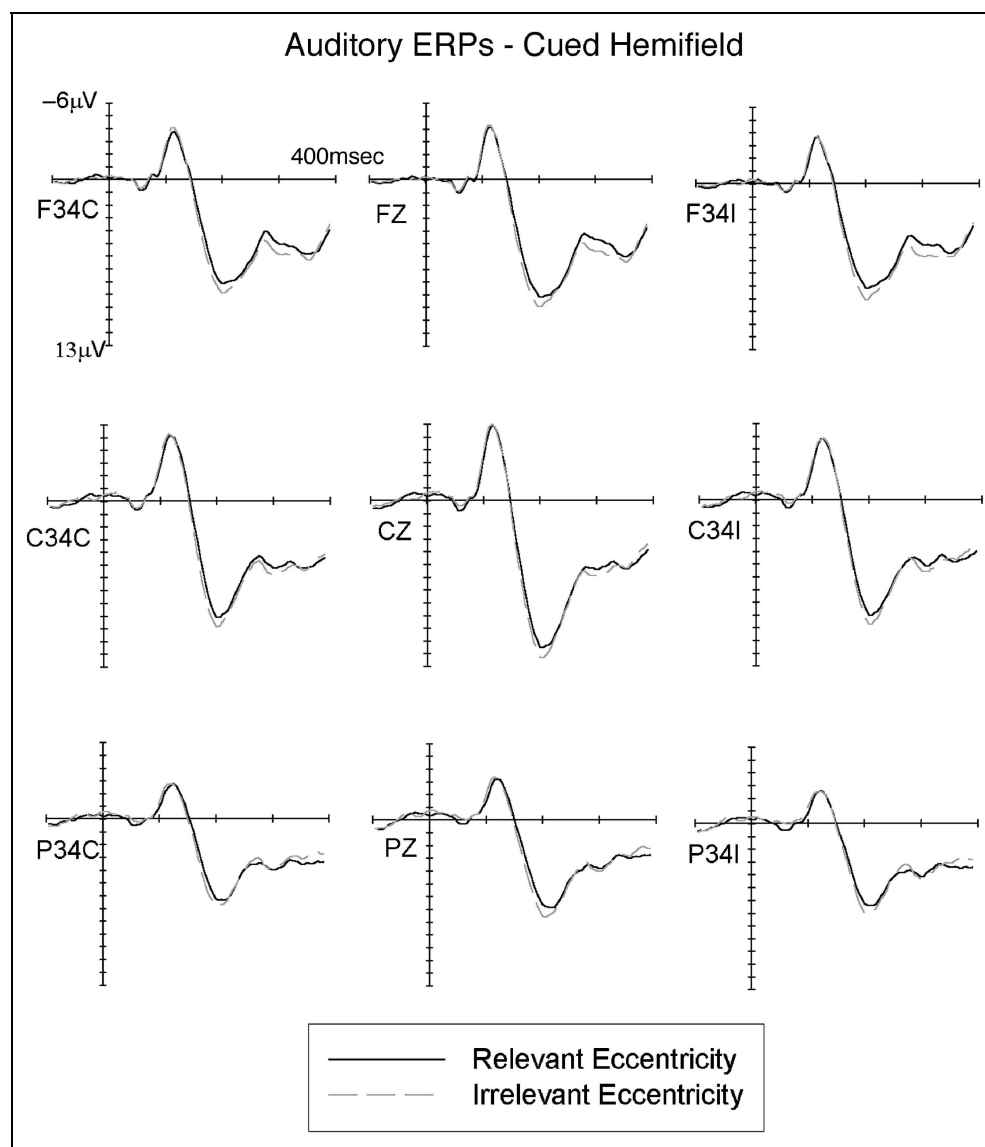
Participants attended to one of four possible stimulus locations (two on the left side, and two on the right side) in order to detect infrequent target stimuli in the relevant modality at this attended location. All other locations had to be ignored, as did all irrelevant modality stimuli, regardless of their location. In Experiment 1, audition was relevant and vision irrelevant, while in Experiment 2 these roles were reversed. Relevant hemifields were cued on a trial-by-trial basis, while the relevant location within the cued hemifield (inner vs. outer) was varied across blocks.

In line with the results of earlier studies demonstrating that unimodal visual and auditory attention can be allocated to circumscribed regions of space within hemifields during visual or auditory tasks (e.g., Teder-Sälejärvi & Hillyard, 1998; Mangun & Hillyard, 1988; Eimer, 1997; Mondor & Zatorre, 1995; Downing &

**Figure 7.** Grand-averaged auditory ERPs elicited in Experiment 2 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to task-irrelevant auditory stimuli presented in the cued hemifield (black solid lines) and in the uncued hemifield (gray dashed lines). Data are collapsed across inner and outer locations.



**Figure 8.** Grand-averaged auditory ERPs elicited in Experiment 2 at midline electrodes, and at sites contralateral (C) and ipsilateral (I) to the side of stimulus presentation, in the 400-msec interval following stimulus onset. ERPs were elicited in response to task-irrelevant auditory stimuli presented within the cued hemifield, and are displayed separately for the eccentricity relevant for the visual task (inner for attend inner blocks; outer for attend outer blocks; black solid lines) and for the task-irrelevant eccentricity (inner for attend inner blocks; outer for attend inner blocks; gray dashed lines).



Pinker, 1985), systematic within-hemifield attentional ERP modulations were found when audition or vision served as the “primary” modality that was currently task-relevant. In Experiment 1, where audition was the task-relevant modality, an attentional negativity was present for ERPs in response to auditory stimuli presented in the cued hemifield relative to uncued-hemifield auditory stimuli, and this effect started on the descending flank of the auditory N1 component (Figure 1). The selection of auditory stimuli at relevant eccentricities “within” the cued hemifield was somewhat delayed (Figure 2), indicating a gradual tuning of spatial attention (see also Teder-Sälejärvi & Hillyard, 1998, for analogous findings in a unimodal auditory experiment). In Experiment 2, where vision was relevant, visual stimuli presented in the cued hemifield elicited enhanced P1, N1, and N2 components relative to visual stimuli on the uncued side (Figure 5). This between-hemifield selection of visual stimuli appeared to precede the selection of visual

stimuli at relevant eccentricities “within” the cued hemifield, as no attentional modulation of the visual P1 component was observed for the within-hemifield analysis, where the earliest effects applied to the N1 component instead (Figure 6). This again suggests a gradual tuning of spatial attention within the primary modality, where selection of the relevant hemifield may precede selection of the relevant eccentricity within this hemifield (see Eimer, 1997, for similar results from a unimodal visual ERP study).

Having demonstrated between- and within-hemifield effects of spatial attention within audition or vision, when serving as the primary task-relevant modality, we turn now to consider the cross-modal effects, concerning the distribution of spatial attention within the “secondary” task-irrelevant modalities. To aid discussion, four different possibilities for how attention might hypothetically be distributed in the currently task-irrelevant modality, in relation to the attentional

focus within the primary modality, are illustrated schematically in Figure 9, for the case where attention in the task-relevant modality has been focused on the left outer location (solid circle). Under this situation, one possibility is that the within-hemifield attentional tuning observed for a task-relevant modality might show full cross-modal transfer to the currently irrelevant modality, leading to identical foci (and spreads) of spatial attention for primary and secondary modalities (Figure 9, top left). This would be directly in line with recent suggestions, stemming from behavioral studies (e.g., Spence et al., 2000; Kennett, Spence, & Driver, in press) and some ERP results (e.g., Eimer et al., 2001, 2002), that cross-modal interactions in spatial attention reflect selection of a particular location at a multimodal level of spatial representation.

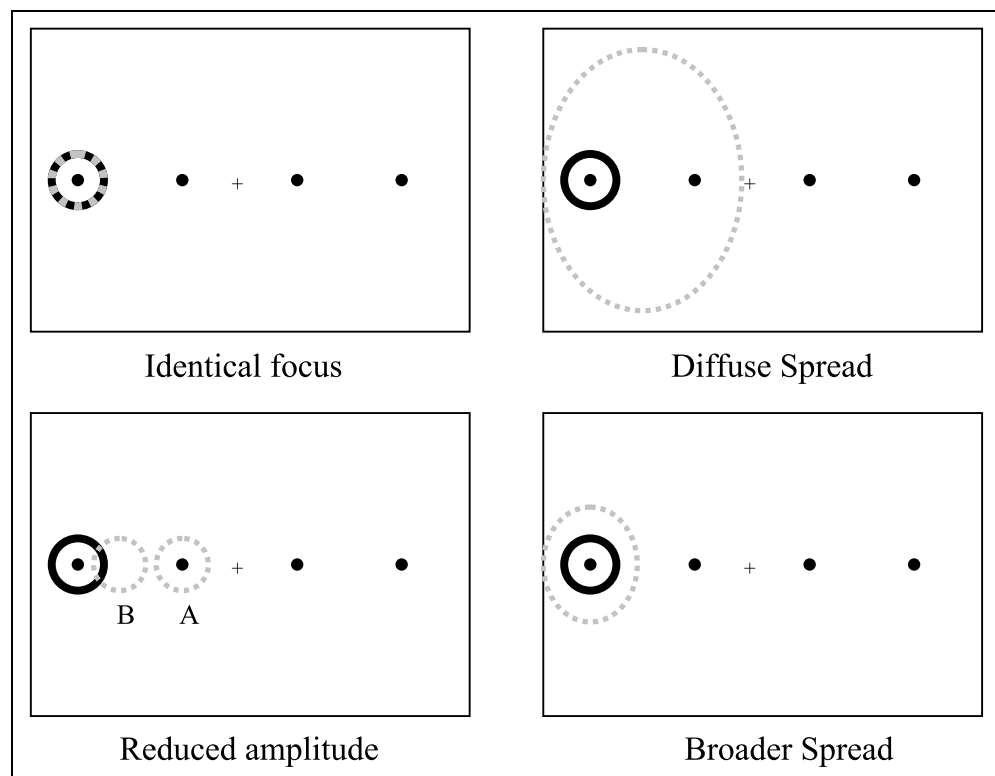
Alternatively, as mentioned previously, attention might in principle be diffusely spread throughout one entire hemifield for the task-irrelevant secondary modality, even when attention is focused at one particular location within that hemifield for the primary modality (Figure 1, top right). Such diffuse cross-modal effects could arguably fit with Kinsbourne's (1975) "hemispheric-activation" account for spatial attention (see *Introduction*).

A third, more intermediate possibility is that shifts of attention to a particular location on one side for a primary task-relevant modality might result in partial or "incomplete" attentional shifts (i.e., with reduced amplitude) within irrelevant modalities. For example,

directing attention to the left outer location for a visual task might potentially result in some concomitant attentional shift in the same leftward direction for audition, but this shift for the secondary modality might be of reduced amplitude. Possible hypothetical consequences of such "incomplete" attentional shifts are illustrated in Figure 9 (bottom left), for the case of a large amplitude reduction (A) that potentially leaves the secondary attentional focus closer to the inner location on that side, and also for the case of a less extreme amplitude reduction (B), where the secondary focus would fall somewhat short of the outer location. Finally, it could, in principle, be the case that although the amplitudes of attentional shifts are equivalent for primary and secondary modalities in terms of the location of peak attention, the secondary attentional focus might remain somewhat broader than the more sharply tuned primary focus (Figure 9, bottom right).

We turn now to consider our cross-modal ERP results in relation to the possibilities depicted schematically in Figure 9. If cross-modal links merely resulted in a diffuse allocation of attention across one entire hemifield for task-irrelevant secondary modalities (Figure 1, top right), then absolutely no within-hemifield attentional modulations should have been observed for visual ERPs in Experiment 1, nor for auditory ERPs in Experiment 2. The present results provide unequivocal evidence against this hypothesis. Recall that in Experiment 1, task-irrelevant visual stimuli presented in the cued hemifield gave rise to enhanced anterior and posterior N1

**Figure 9.** Schematic illustration of four hypothetical possibilities for the spatial distribution of attention for a secondary modality under conditions where attention is directed to the outer left location for a primary modality task. Solid black circles indicate the focus of attention for a primary modality, dashed gray lines indicate the hypothetical attentional focus for the secondary modality. Top left: Identical attentional foci (and spread) for primary and secondary modalities. Top right: Secondary focus diffusely spread across an entire hemifield. Bottom left: Amplitude of attentional shift reduced for secondary modality (A = large reduction; B = smaller reduction). Bottom right: Common attentional focus but broader spread for secondary modality. See main text of discussion for further details.



components relative to visual stimuli on the uncued side (Figure 3), thus confirming results from many previous ERP studies investigating between-hemifield cross-modal attention effects (Teder-Sälejärvi et al., 1999; Eimer & Schröger, 1998; Hillyard et al., 1984). The critical new result was that attentional modulations of the visual N1 by the auditory task were also observed for the “within-hemifield” comparisons. That is, N1 components to visual stimuli at the particular eccentricity that was currently relevant for the auditory task were enhanced, relative to N1 amplitudes elicited by visual stimuli in the same cued hemifield, but at the irrelevant eccentricity (Figure 4).

Recall also that, in Experiment 2, task-irrelevant auditory stimuli presented in the hemifield that was cued for the visual task gave rise to an enhanced negativity starting on the descending flank of the N1 component (Figure 7), again confirming results from previous visual/auditory cross-modal ERP studies where attentional selectivity was investigated between hemifields (Teder-Sälejärvi et al., 1999; Eimer & Schröger, 1998; Hillyard et al., 1984). More importantly, and in line with the results obtained here for visual ERPs in Experiment 1, a critical new result was that auditory attentional negativities during a visual task were also obtained in the “within-hemifield” comparison, for ERPs elicited by auditory stimuli at the location that was currently relevant for the visual task, relative to ERPs for auditory stimuli presented within the same cued hemifield, but at the task-irrelevant location (Figure 8).

The present results thus convincingly rule out the hypothesis that the focus of attention for secondary modalities is diffusely spread across an entire hemifield (Figure 9, top right). They may also shed some initial light on the other possibilities illustrated in Figure 9, although further work with extensions of the manipulations introduced here may be required to conclude decisively in favor of only one account. According to the “incomplete attentional shift” hypothesis (Figure 9, bottom left), the amplitudes of secondary attentional shifts may be reduced relative to attentional shifts for the currently relevant primary modality. If such reductions were substantial, secondary inner stimuli on the cued side might fall within the secondary attentional focus when attention is directed towards outer locations in the primary modality (see (A) in Figure 9, bottom left), while secondary outer stimuli would effectively be unattended under both attend inner-primary and attend outer-primary conditions. This should be reflected in Stimulus eccentricity  $\times$  Within-hemifield attention interactions for secondary modalities. However, no such interactions were obtained in either experiment here, suggesting that the cross-modal within-hemifield attentional effects applied comparably for stimuli at inner as well as outer locations. These findings seem inconsistent with a strong version of the “incomplete attentional shift” hypothesis.

If the reduction of shift amplitudes for secondary modalities was less pronounced, the secondary focus of attention might be closer to outer than inner stimuli under attend outer-primary instructions (see (B) in Figure 9, bottom left), and vice versa for attend inner-primary instructions. This possibility could thus be reconciled with the observed presence of cross-modal within-hemifield attention effects, and the absence of Stimulus eccentricity  $\times$  Within-hemifield attention interactions. However, if shift amplitudes were reduced for secondary modalities, effects of within-hemifield attention on auditory and visual ERPs should presumably be more pronounced when the respective modality is primary (i.e., with attention fully focussed on task-relevant locations) than when the same modality is secondary (and attentional shifts are incomplete). To investigate this possibility, we compared within-hemifield attention effects for auditory or visual ERPs obtained under conditions when that respective modality was either primary (task-relevant) or secondary (irrelevant). These across-experiment mixed analyses (with task relevance as the between-subject factor) showed no significant Task relevance  $\times$  Within-hemifield attention interactions for the visual N1 component in the 120–160 and 160–200 msec intervals, all  $F(2,22) < 1.2$ . That is, the N1 modulations caused by within-hemifield attention were not affected by whether vision was task-relevant or not. Similarly, no Task relevance  $\times$  Within-hemifield interactions were observed for auditory ERPs at the lateral anterior and central electrodes in the Nde interval (130–200 msec poststimulus; all  $F(2,22) < 1.8$ ).<sup>2</sup> In contrast, significant interactions were present in the subsequent 200–300 msec interval for auditory ERPs at the lateral anterior, lateral central, and midline sites, and for visual ERPs at the lateral central sites, all  $F(2,22) > 11.3$ ; all  $p < .003$ , reflecting larger late attentional negativities under conditions where the respective modality was relevant. This is consistent with previous findings that these later components do depend substantially on task relevance of the particular modality stimulated (see Eimer, 2001, for review), not just on stimulus location in relation to spatial attention.

The fact that early within-hemifield attention effects were present for currently irrelevant modalities is inconsistent with the “diffuse spread” account (Figure 9, top right); the additional observation that these within-hemifield effects were statistically equivalent regardless of whether the modality in question was currently task-relevant does not appear to fit naturally with any suggestions that the amplitudes of attentional shifts for secondary modalities might be reduced relative to primary modalities (Figure 9, bottom left). The results are entirely consistent with our working hypothesis that the spatial allocation of attention for a visual or auditory task may show full cross-modal transfer to the other currently irrelevant modality (Figure 9, top

left). However, it should be acknowledged that the present findings cannot decisively rule out the possibility that the secondary attentional focus may be somewhat broader than the more sharply tuned primary focus (Figure 9, bottom right). To investigate any such subtle differences in the tuning of attention across modalities within hemifields, attended and unattended stimulus locations within the same hemifield will need to be more closely spaced than in the present study (where they were separated by 31°) and indeed numerous within-hemifield locations may have to be compared within the same study.

In summary, the present study has demonstrated that when covert spatial attention is endogenously allocated to one specific location in a given hemifield, for an auditory or visual task, within-hemifield ERP effects of spatial attention can also be found for a currently irrelevant modality. This leads to systematic within-hemifield attentional modulations of visual ERPs when only audition is task-relevant, and of auditory ERPs when only vision is task-relevant. Such a pattern of results unequivocally rules out the possibility that cross-modal effects of endogenous spatial attention are diffuse, applying to an entire hemifield. Overall, the fact that the spatial distribution of attention can transfer across modalities even within hemifields provides further support for the emerging idea (see Eimer & Van Velzen, 2002; Eimer et al., 2002; Spence et al., 2000; Farah et al., 1989; Kennett et al., in press) that cross-modal interactions in spatial attention may reflect location-selection at a multimodal level of spatial representation.

## METHODS

### Participants

Fourteen paid volunteers participated in Experiment 1, and 13 volunteers in Experiment 2. One participant in Experiment 1 had to be excluded because of an inability to perform the auditory task, one other participant was excluded due to excessive eye-blink artifacts. One participant in Experiment 2 had to be excluded because of poor eye-fixation control in the cue–target interval (see below). Thus, 12 participants remained in the sample for each of the experiments. In Experiment 1, participants (6 men, 6 women, all right-handed) were aged 20–40 years (mean age: 27 years). In Experiment 2, participants (7 men, 5 women, all right-handed) were aged 19–32 years (mean age: 25 years). All participants had normal or corrected vision and normal hearing by self-report.

### Stimuli and Apparatus

Participants sat in a dimly lit experimental chamber, with a head-mounted microphone positioned 2 cm in front of the mouth. A computer monitor was placed centrally in

front of the participant at a viewing distance of 55 cm. Central symbolic visual cue stimuli consisted of two adjacent triangles, covering a visual angle of 3.5° × 2.5°, and presented centrally at the bottom of the computer screen at an angle of about 30° below eye level. One of the triangles was red, the other blue, and they always pointed in opposite directions ('> <' or '< >'). These different cue arrangements were equiprobable and randomly distributed in each block. A central fixation cross, located in the space between the two triangles, was continuously present on the computer screen throughout the experimental blocks. Auditory stimuli were bursts of white noise (200 msec duration, including 5 msec rise and 5 msec fall times; amplitude 80 dB SPL) presented from one of four loudspeakers (two on the left and two on the right of fixation). Visual stimuli were 200 msec illuminations of one of four ensembles of green LEDs (two on the left and two on the right of fixation), consisting of six segments arranged in a circle plus one central segment. The angular size of each LED was 0.47°, the diameter of the circle was 1.7°. The four loudspeakers and the four LED ensembles were each placed on a table either 21° to the left or right of fixation (inner positions), or 52° to the left or right of fixation (outer positions). These positions were laid out on a virtual semicircle centered on the subject's head to allow a constant viewing distance of about 60 cm for each of the four positions. The loudspeaker and LED cluster at each of the four positions were located in close spatial register with each other.

Auditory nontarget (standard) stimuli consisted of a continuous 200 msec white noise burst from one of the peripheral loudspeakers. For the rare auditory "odd-ball" target stimuli, the noise was interrupted after 90 msec by a 20-msec silent interval, after which the noise was turned on again for 90 msec (to produce a stimulus that included a "gap"). Visual nontarget (standard) stimuli consisted of a continuous 200 msec illumination of one LED ensemble. For infrequent visual "gap" stimuli (that could serve as targets), this LED was briefly switched off. In Experiment 1 (where visual stimuli were irrelevant), a gap of 10 msec occurred 95 msec after LED onset, and was followed by another 95 msec illumination. In Experiment 2 (where detection of visual gap stimuli at the relevant location was now the prescribed task), gaps were 30 msec (preceded and followed by two 85-msec LED illumination periods) for visual gap stimuli presented at one of the two inner positions, and 100 msec (preceded and followed by two 50-msec LED illumination periods) for visual gap stimuli presented at one of the two outer positions. Different gap durations were employed for visual targets at inner and outer locations because piloting the visual task had shown that visual gaps were much harder to detect at outer relative to inner locations, and we sought to minimize this difference (although note that all the critical ERP findings concern standard stimuli in each

modality, with no gap). Vocal response-onset times were measured with a voice key.

## Procedure

Both experiments consisted of 12 experimental blocks, with 164 trials per block. A short break was included after 82 trials of each block, and participants could initiate the second run of 82 trials for this block by pressing a response button. Each trial started with the presentation of a central symbolic visual cue (100 msec duration), which was followed after an interval of 600 msec equiprobably by an auditory or a visual peripheral stimulus (200 msec duration). Intertrial interval was 1000 msec.

In Experiment 1, the task was to respond vocally (by saying “yes”) whenever an auditory gap target was presented at just the relevant eccentricity (inner or outer), and in only the relevant hemifield (left or right) that had been indicated by the central cue on that trial. Auditory events at the other three locations (including any with gaps) were to be ignored, as were any visual events regardless of their location. The relevant hemifield for each trial was cued by the direction of either the red or the blue central triangle. For half of the participants, blue triangles indicated the attended side, while red triangles were relevant for the other half of the participants. Relevant left-pointing and right-pointing triangles were presented with equal probability to the left or right of the fixation cross.

The relevant eccentricity to monitor for gap targets in the relevant modality (i.e., inner or outer on the cued side) was varied across blocks. In six successive blocks (attend inner condition), participants were instructed to attend to either the left or the right inner position, with the relevant side indicated by the central precue. In the other six successive blocks (attend outer condition), participants had to direct attention to either the left or the right outer location. The order in which these two conditions were delivered was counterbalanced across participants, and instructions specifying the relevant eccentricity (i.e., inner outer) were displayed on the computer screen prior to the start of each block.

In 128 trials per block, an auditory or visual nongap stimulus was presented with equal probability and in random order at any one of the four positions. These stimuli were preceded with equal probability by attend left or attend right cues. Eight trials per block were delivered for each of the 16 combinations of modality (vision vs. audition), side (left vs. right), eccentricity (inner vs. outer), and cue direction (left vs. right). In the remaining randomly intermingled 36 trials, gap stimuli were presented. Auditory gap stimuli were presented on 28 trials. Sixteen of these (eight left, eight right) were presented on the cued side and at the relevant eccentricity, and thus required a response. The remaining 12 auditory gap targets were presented

on the uncued side, at the irrelevant eccentricity, or both, and thus required no response. Eight irrelevant visual gap stimuli were also included in each block (one for each combination of side, eccentricity, and cue direction).

Experiment 2 had the same design and procedure as Experiment 1, except that now vision was task-relevant. Participants had to respond whenever a visual gap target was presented at the relevant eccentricity, in just the cued hemifield, ignoring visual stimuli elsewhere and all auditory stimuli regardless of their location. Visual gap stimuli were presented on 28 trials (16 trials with visual targets at relevant locations), while auditory gap stimuli were presented on only eight trials per block.

In both experiments, participants were instructed to direct their covert attention to the relevant location (inner or outer, on the left or right, with relevant eccentricity varied between blocks but side on a trial-by-trial manner) in just the relevant modality, in order to respond as quickly and accurately as possible to auditory (Experiment 1) or visual (Experiment 2) target stimuli presented at this location, while withholding responses to all other stimuli. They were explicitly encouraged to maintain central eye fixation throughout the trials. Several training blocks were run prior to the beginning of each of the two task conditions. Eye movements were closely monitored during these training blocks. Whenever the horizontal EOG revealed that participants did not maintain central eye fixation, they were reminded again of the necessity of continuously fixating the central cross throughout an experimental block. Additional training blocks were run until fixation control was regarded as satisfactory. EOG was assessed and recorded throughout the experiment.

## Recording and Data Analysis

EEG was recorded with Ag–AgCl electrodes and linked-earlobe reference from F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, and P8 (according to the 10-20 system), and from OL and OR (located halfway between O1 and P7, and O2 and P8, respectively). Horizontal EOG was recorded bipolarly from the outer canthi of both eyes. The impedance for all electrodes was kept below 5 k $\Omega$ . The amplifier bandpass was 0.1 to 40 Hz, and no additional filters were applied to the EEG waveforms. EEG and EOG were sampled with a digitization rate of 200 Hz and stored on disk. Voice-onset times were measured for each vocal response.

EEG and EOG were epoched off-line into 1400-msec periods, starting 100 msec prior to cue onset, and ending 600 msec after the onset of the peripheral stimulus. Trials with eye blinks (Fpz exceeding  $\pm 60$   $\mu$ V relative to baseline), horizontal eye movements (HEOG exceeding  $\pm 30$   $\mu$ V relative to baseline), or other artifacts (a voltage exceeding  $\pm 60$   $\mu$ V at any electrode location



relative to baseline) obtained in the final 600 of this interval were excluded from analysis, as were trials where any horizontal eye movements were detected in the cue–target interval. In addition, averaged HEOG waveforms in response to cues directing attention to the left versus right hemifield, obtained both in attend inner and attend outer blocks, were scored for systematic deviations of eye position, indicating any residual tendencies to move the eyes towards the cued location. A residual HEOG deviation exceeding  $\pm 2 \mu\text{V}$  led to the disqualification of one participant in Experiment 2.

In both experiments, the EEG obtained in response to visual and auditory nontarget stimuli was averaged for all combinations of task condition (attend inner vs. attend outer), stimulus eccentricity (inner vs. outer), cueing (stimulus presented at the cued side vs. stimulus presented at the uncued side), and stimulus side (left vs. right). Only nontarget trials (i.e., stimuli without any gap) were included to avoid contamination by vocal responses to gap targets. Trials where false-positive vocal responses were recorded on nontarget trials were also excluded from analysis. Auditory ERPs were analyzed within two successive time windows between 130 and 200 msec poststimulus (early Nd; Nde), and between 200 and 300 msec poststimulus (late Nd; Ndl). Visual ERPs were analyzed within the following post-stimulus time windows: 90–130 msec (P1); 120–160 msec (anterior N1); 160–200 msec (posterior N1); 200–300 msec (Nd).

Statistical analyses were based on mean amplitude values obtained relative to a 100-msec prestimulus baseline at lateral anterior sites (F7/8, F3/4, FC5/6), lateral central sites (T7/8, C3/4, CP5/6), lateral posterior sites (P7/8, P3/4, OL/R), and at midline electrodes (Fz, Cz, Pz). Two successive analyses were conducted. First, an ANOVA was run with the factors of task condition (attend inner vs. attend outer blocks), cueing (stimulus at cued vs. uncued side), stimulus eccentricity (inner vs. outer), stimulus side (left vs. right), electrode site, and recording side (for lateral electrodes only). Then, only ERPs obtained in response to stimuli presented “within just the cued hemifield” were submitted to additional ANOVAs, omitting the factor cueing. These analyses included the factors stimulus eccentricity, stimulus side, electrode site, and recording site, as well as the new factor within-hemifield attention (stimulus presented at currently relevant vs. irrelevant eccentricity within the cued hemifield), which replaced the factor task condition. Results due trivially to stimulus and anatomical laterality are not reported. Whenever interactions between attention and electrode site were found (for brevity, these are not all reported in full), additional analyses were conducted for single electrode sites. For vocal responses, repeated-measures ANOVAs were performed on response latencies and on arcsin-transformed error rates for the factors of task condition and target location (left vs. right).

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## Notes

1. Similarly, no significant Stimulus eccentricity  $\times$  Within-hemifield attention interactions were found in the earlier 120–160 msec time window, although this interaction approached significance at the lateral central electrodes,  $F(1,11) = 4.5$ ;  $p < .06$ .
2. The fact that effects of within-hemifield attention on auditory ERPs reached significance in the Nde interval for Experiment 2 (when vision was primary and task-relevant), but not in Experiment 1 (where audition was the relevant modality), might suggest that, if anything, within-hemifield auditory attention tended to be more effective when auditory stimuli were irrelevant and vision was primary. However, this tendency was not substantiated by significant interactions in the across-experiment analysis.

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